Practical Applications
of Space Systems

Supporting Paper 1

Weather and Climate

A Panel Report Prepared for the

Space Applications Board

Assembly of Engineering

National Research Council

PREFACE

In November 1973, the National Aeronautics and Space Administration (NASA) asked the National Academy of Engineering* to conduct a summer study of future applications of space systems, with particular emphasis on practical approaches, taking into consideration socioeconomic benefits. NASA asked that the study also consider how these applications would influence or be influenced by the Space Shuttle System, the principal space transportation system of the 1980's. In December 1973, the Academy agreed to perform the study and assigned the task to the Space Applications Board (SAB).

In the summers of 1967 and 1968, the National Academy of Sciences had convened a group of eminent scientists and engineers to determine what research and development was necessary to permit the exploitation of useful applications of earth-oriented satellites. The SAB concluded that since the NAS study, operational weather and communications satellites and the successful first year of use of the experimental Earth Resources Technology Satellite had demonstrated conclusively a technological capability that could form a foundation for expanding the useful applications of space-derived information and services, and that it was now necessary to obtain, from a broad cross-section of potential users, new ideas and needs that might guide the development of future space systems for practical applications.

After discussions with NASA and other interested federal agencies, it was agreed that a major aim of the "summer study" should be to involve, and to attempt to understand the needs of, resource managers and other decision-makers who had as yet only considered space systems as experimental rather than as useful elements of major day-to-day operational information and service systems. Under the general direction of the SAB, then, a representative group of users and potential users conducted an intensive two-week study to define user needs that might be met by information or services derived from earth-orbiting satellites. This work was done in July 1974 at Snowmass, Colorado.

For the study, nine user-oriented panels were formed, comprised of present or potential public and private users, including businessmen, state and local government officials, resource managers, and other decision-makers. A number

*Effective July 1, 1974, the National Academy of Sciences and the National Academy of Engineering reorganized the National Research Council into eight assemblies and commissions. All National Academy of Engineering program units, including the SAB, became the Assembly of Engineering.

of scientists and technologists also participated, functioning essentially as expert consultants. The assignment made to the panels included reviewing progress in space applications since the NAS study of 1968* and defining user needs potentially capable of being met by space-system applications. User specialists, drawn from federal, state, and local governments and from business and industry, were impaneled in the following fields:

Panel 1: Weather and Climate
Panel 2: Uses of Communications
Panel 3: Land Use Planning
Panel 4: Agriculture, Forest, and Range
Panel 5: Inland Water Resources
Panel 6: Extractable Resources
Panel 7: Environmental Quality
Panel 8: Marine and Maritime Uses
Panel 9: Materials Processing in Space

In addition, to study the socioeconomic benefits, the influence of technology, and the interface with space transportation systems, the following panels (termed interactive panels) were convened:

Panel 10: Institutional Arrangements
Panel 11: Costs and Benefits
Panel 12: Space Transportation
Panel 13: Information Services and Information Processing
Panel 14: Technology

As a basis for their deliberations, the latter groups used needs expressed by the user panels. A substantial amount of interaction with the user panels was designed into the study plan and was found to be both desirable and necessary.

The major part of the study was accomplished by the panels. The function of the SAB was to review the work of the panels, to evaluate their findings, and to derive from their work an integrated set of major conclusions and recommendations. The Board's findings, which include certain significant recommendations from the panel reports, as well as more general ones arrived at by considering the work of the study as a whole, are contained in a report prepared by the Board.**

It should be emphasized that the study was not designed to make detailed assessments of all of the factors which should be considered in establishing priorities. In some cases, for example, options other than space systems for accomplishing the same objectives may need to be assessed; requirements for

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*National Research Council. *Useful Applications of Earth-Oriented Satellites, Report of the Central Review Committee*. National Academy of Sciences, Washington, D.C., 1969.

**Space Applications Board, National Research Council. *Practical Applications of Space Systems*. National Academy of Sciences, Washington, D.C., 1975.

institutional or organizational support may need to be appraised; multiple uses of systems may need to be evaluated to achieve the most efficient and economic returns. In some cases, analyses of costs and benefits will be needed. In this connection, specific cost-benefit studies were not conducted as a part of the two-week study. Recommendations for certain such analyses, however, appear in the Board's report, together with recommendations designed to provide an improved basis upon which to make cost-benefit assessments.

In sum, the study was designed to provide an opportunity for knowledgeable and experienced users, expert in their fields, to express their needs for information or services which might (or might not) be met by space systems, and to relate the present and potential capabilities of space systems to their needs. The study did not attempt to examine in detail the scientific, technical, or economic bases for the needs expressed by the users.

The SAB was impressed by the quality of the panels' work and has asked that their reports be made available as supporting documents for the Board's report. While the Board is in general accord with the panel reports, it does not necessarily endorse them in every detail.

The conclusions and recommendations of this panel report should be considered within the context of the report prepared by the Space Applications Board. The views presented in the panel report represent the general consensus of the panel. Some individual members of the panel may not agree with every conclusion or recommendation contained in the report.

PANEL ON WEATHER AND CLIMATE

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INTRODUCTION

During the 1974 Summer Study on Space Applications, the Panel on Weather and Climate undertook a review of existing operational and R&D programs. The Panel was impressed with the existing systems and the degree to which they have become an integral part of the meteorological program in the United States. Low-altitude and geostationary satellites provide timely and essential data to the operational forecasts of the National Meteorological Center; a carefully considered R&D program is directed toward the long-range improvement of the operational system. The National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) are both to be congratulated on the success of the meteorological satellite program.

In the field of meteorology, the existing space applications program has been constructively responsive to national initiatives. One set of goals was advanced by the Panel on Meteorology during the 1967-68 Summer Study on Space Applications.* The recommendations prepared during that study follow, together with an indication of the current status of each:

1. The central recommendation of the 1967-68 report called for NASA to "...continue to direct its meteorological satellite program to meeting the observational requirements of GARP (Global Atmospheric Research Program) and the World Weather Watch programs...."** To implement this program, and particularly to support the First GARP Global Experiment (FGGE), it was proposed to develop an integrated space-based system to provide global coverage in the late 1970's for synoptic-scale forecasting.*** There were to be four geostationary meteorological satellites and one or two sun-synchronous near-earth satellites, with associated ground (ocean buoy) and airborne (balloon) platforms to be interrogated from space.

It is now planned that there will be five geostationary satellites in operation by early 1978, two of which are to be operated by the U.S. (the first was successfully put into operation in May 1974), one by Japan, one by the European Space Agency (ESA), and one by the U.S.S.R. The technical characteristics of these satellites are being coordinated for optimum

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*National Research Council. *Useful Applications of Earth-Oriented Satellites: Report of the Panel on Meteorology* (Panel 4). National Academy of Sciences, Washington, D.C., 1969.

**Report of the Panel on Meteorology, p. 5.

***See Table I (p. 5) for definition of meteorological scales.

compatibility of the information produced and for data-relay capabilities. Two sun-synchronous near-earth satellites with advanced sounding systems and platform-location and data-relay capabilities are scheduled for launch in late 1977 and early 1978. Instrumented drifting buoys, constant-level balloons, and large carrier balloons with wind-finding dropsonde dispensers are under active development; extensive field tests will be carried out in 1974-75 in conjunction with the NIMBUS-F satellite. Costs are anticipated to be within those recommended in the 1967-68 study in order to make these techniques economically viable. *The first recommendation of the 1967-68 study is nearing fulfillment.*

2. A second major recommendation called for the development of a fully integrated meteorological geosynchronous satellite to be available by 1971. Both visible and infrared images were to be displayed in real time, and equipment was called for which would be able to present time-lapse views of the images.*

The NASA and NOAA Synchronous Meteorological Satellite (SMS) and Geostationary Operational Environmental Satellite (GOES) series were inaugurated in May 1974 with high-resolution visible and medium-resolution infrared (IR) imaging capability. The first satellite is performing to specification. A limited operational ground display system has been developed and implemented, and equipment for high-resolution display and picture production is also operating on an experimental basis. Various methods of time-lapse display of images have been used or are in process of development. *This recommendation has been implemented.*

3. A third recommendation called for IR and microwave vertical temperature sounders to be used on both polar-orbiting and geostationary satellites and to be capable of satisfying known data requirements for synoptic-scale numerical weather forecasting.

The IR sounders are in operational use on polar-orbiting satellites. However, the accuracy of temperature measurement is not adequate: errors average between 2°C and 3°C compared with a requirement of 1°C. A microwave sounder was flown successfully on NIMBUS-5 and it is planned to include microwave sounders, along with advanced IR sounders (more channels and higher resolution) on a new operational series of low-altitude satellites starting in 1977-78. IR and microwave sounders have not yet been flown on geostationary satellites. *Thus, the implementation of this recommendation is still incomplete.*

4. The final two recommendations of the 1967-68 study dealt with development of light-weight, safe, low-cost meteorological packages for constant-level balloons, and for techniques of sounding the atmosphere through clouds by use of microwaves. *The required developments are either proven or about to be tested, and the outlook is very positive for useful operational systems.*

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*Report of the Panel on Meteorology, p. 5.

In some other areas the meteorological satellite program has moved more rapidly than could have been anticipated in 1967-68. For example, data transmitted by geostationary satellites are now being used operationally by NOAA to determine atmospheric winds. This technique, which was not foreseen in 1967, has proven to be valuable in the preparation of weather forecasts.

It has already been noted that developments in the meteorological space applications program have been closely coordinated with the objectives of the World Weather Watch program, especially GARP. Detailed plans for a meteorological Global Observing System are being readied for FGGE. Much of the current high-priority R&D in the meteorological space applications program is being undertaken to contribute to the success of FGGE.

It is important to note, however, that the goals of meteorology are broader than the assessment of the feasibility of extending synoptic-scale forecasting. A major statement of these goals was set forth in a report published by the Committee on Atmospheric Sciences of the National Academy of Sciences.* These goals were (1) to extend useful forecasting capability, (2) to contribute to the development of the capability to manage and control the concentrations of air pollutants, (3) to establish mechanisms for the national examinations of deliberate and inadvertent means for modifying weather and climate, and (4) to reduce social, economic, and human losses caused by weather.

The recommendations in the present study deal explicitly with goals (1) and (4). They also deal with goals (2) and (3) in areas where the monitoring of associated meteorological parameters from space has contributed to the development of useful management or modification techniques.

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*Committee on Atmospheric Sciences, National Research Council. *The Atmospheric Sciences and Man's Needs: Priorities for the Future*. National Academy of Sciences, Washington, D.C., 1971.

SPACE APPLICATIONS TO METEOROLOGY

Space and time scales of motion in operational meteorology range over a wide spectrum from local, transitory weather phenomena to global, climatic changes, as outlined in Table I.

Table I Range of Meteorological Scales

Scale	Approximate Time Scale	Approximate Area of Influence
Local present weather	0 to 2 hours	150 km
Short range (mesoscale)	2 to 12 hours	1000 km
Synoptic	1 day to 1 week	Hemispheric
Long range and climate	2 weeks or more	Global

The observational methods and the prediction techniques vary markedly throughout the range from the smallest to the largest scale.

PRESENT-WEATHER DISPLAY

In its 1971 report, the Committee on Atmospheric Sciences of the National Academy of Sciences placed a high priority on the development of comprehensive systems for monitoring present weather, with the information being made continuously available to broad categories of users. Input data might be derived from satellite and radar observations and from a network of low-cost, unmanned weather stations interrogated by computer. The combined output could be distributed to the general public and other users by television or other communication systems.

Information on localized weather for periods of up to 2 hours is becoming increasingly important to the decision-making processes of a wide variety of users. Additionally, the display of local present weather is vital in alerting

the public to hazardous weather. Space platforms offer a practical source of data for the timely display of present-weather information and a possible vehicle for the rapid dissemination of warnings.

The wide demand for present-weather data has been demonstrated by the extensive use of the Automatic Picture Transmission (APT) system, now part of the NOAA satellite series. Over 1,000 users purchased or constructed specialized ground equipment in order to receive these pictures. This represents a voluntary expenditure of approximately $10 million. Since this weather data is obtained from low-altitude satellites, it is available only twice daily. The continuous flow of data from geostationary satellite systems would increase manyfold the utility of present-weather information.

RECOMMENDATION - The Panel on Weather and Climate recommends the development of a low-cost readout system from three-axis-stabilized geostationary satellites for the display of local present weather in real time. This could be part of a broad present-weather information network. To test the effectiveness of such a system, the Panel recommends that a present-weather pilot project be undertaken in a region that includes both urban and rural areas.

SHORT-RANGE FORECASTS

A simple extrapolation of the movement of small-scale weather systems, such as thunderstorms, will usually provide a successful weather forecast for only a short period of time, generally 1 to 2 hours. Beyond this, it will be necessary for meteorologists to devise forecasting methods to modify extrapolation. The result will be to change in an appropriate way projections of the direction of motion, the speed, and the rate of development of existing weather systems. With the addition of new forecasting techniques, it is probable that forecasts can be effectively extended to a range of from 3 to 6 hours.

In developing these forecasting techniques, it will be important to have information about the vertical structure of the atmosphere in particular local areas where short-term forecasts are to be prepared. An IR-sounding capability from a geostationary platform would be an effective way of obtaining such data. The additional provision of three-axis-stabilization would improve by one order of magnitude the time available for observation and therefore would greatly enhance the capability of the system.

Extending forecasts into the 6-hour to 12-hour range will be a more difficult problem and will require increasingly sophisticated models and more extensive observations, especially in the planetary boundary layer. Various experimental studies on this time scale will need to be undertaken. NOAA has recently begun to develop plans for a Severe Environmental Storm and Mesoscale Experiment (SESAME) to be carried out over a 3-year period beginning in 1977 or 1978. Satellite support of such experimental programs is, of course, highly desirable.

RECOMMENDATION - The Panel recommends that NASA develop IR-sounding capability from the geostationary Synchronous Meteorological Satellite in order to support the development of short-range forecasts of local weather. The development of a three-axis-stabilized geostationary platform will substantially improve the value of this system.

SYNOPTIC FORECASTS

The synoptic-scale dynamics of the atmosphere are becoming better understood through international efforts such as GARP. These and similar efforts have made it possible to simulate the general characteristics of the global circulation of the atmosphere by numerical models for periods of 1 week or longer. Hemispheric operational versions of such models, which have more demanding data requirements, have led over the last 15 years to an extension of the effective predictability of synoptic-scale weather from 2 days to 3 days and have permitted the National Weather Service to provide general outlooks of the weather 4 and 5 days in advance.

To extend synoptic forecasting capabilities to 5 days or beyond within the next decade, a world-wide atmosphere-ocean observing system is an absolute necessity. By the early 1980's GARP results should give better insight into the possibilities of extending synoptic-scale forecasts beyond 5 days and will also provide a critical assessment of the observational requirements necessary to support such extended forecasts.

The costs associated with operating a global land-ocean-based synoptic observation network are prohibitively high, on the order of $1 billion or more per year. It is obvious that a more effective alternative is a mix of existing land-ocean-based observations and those from a satellite system; this mixed observing system should be capable of monitoring the atmosphere to measure the vertical temperature and humidity structure, the distribution and motion of clouds (from which atmospheric winds can be determined), and sea-surface temperature. An extensive data-relay capability for remote, earth-based automatic stations is also required.

RECOMMENDATION - The Panel on Weather and Climate recommends (1) continued support for GARP in order to assess the possibilities of extending synoptic-scale forecasts; (2) continued R&D effort to improve temperature and humidity soundings, measurements of sea-surface temperatures, measurements of winds using cloud displacements in order to meet the accuracy and resolution requirements set forth for FGGE in 1978-79; and (3) continued R&D efforts toward the use of space techniques to provide wind profiles in the equatorial zone with better vertical resolution than is now possible by cloud-tracking methods, inasmuch as the mixed balloon and satellite observing subsystem planned for FGGE may not lend itself to operational use.

LONG-RANGE WEATHER AND CLIMATE PREDICTION

It now appears that the ability to predict determinately the state of the atmosphere cannot be extended beyond approximately 2 weeks. Hence, the ability to make longer-range forecasts, if possible, may have to be handled in a statistical manner. This implies that meteorology will have to develop a different set of mathematical and descriptive tools if it is to attack the problem of long-range weather and climate prediction. This effort is now in its infancy.

A treatise is not undertaken here concerning the vital importance of the ability to predict weather on the time scales of months, seasons, and years. Suffice it to say, the consensus of the Panel is that this capability is desperately needed by a growing civilization that has seriously strained its food

supplies, natural resources, and distribution systems. Substantial efforts in long-range weather and climate prediction must now begin in order to aid man in coping with the consequences of climatological vagaries (e.g., failure of food and fiber crops).

The development and application of a method of long-range weather and climate prediction require a comprehensive understanding of the interactions of the land-air-ocean system. In order to elucidate these interactions, a capability must be developed to observe all important aspects of this complex system. Fortunately, many of the necessary observations are now or will soon be taken on a routine, operational basis (e.g., atmospheric temperature profiles, water-vapor content, snow-ice cover, and cloud cover). This fortuitous circumstance is a direct result of satellite capabilities developed for GARP. However, some necessary observations are not now being obtained. For instance, there is a need to monitor the energy budget of the earth, for it is the net energy (incoming minus outgoing) that is available to drive the system. For the same reason, the surveillance of the world's oceans must be greatly improved, for their great heat capacity and inertia have an importance influence on the atmosphere. Thus, it is important to know the heat content and field of motion of the mixed layer and of the surface winds.

The parameters that characterize the climate of the land-air-ocean system must be observed on a global basis over time periods ranging from years to decades. Such observations are perhaps the key to development and verification of predictions of climate. Satellites and related systems offer the only cost-effective hope of obtaining these data but, because of the requirements for longtime records, stringent demands will be imposed on sensor stability, reliability, and calibration. The huge amount of data to be collected requires a data-management capability that is not now in existence. (See section entitled "DATA MANAGEMENT," page 17.) Finally, it must be noted that effective pursuit of a climate prediction capability will require an explicit management commitment at the highest level of government.

RECOMMENDATIONS - The Panel recommends that (1) a program of measuring the global radiation budget must be instituted as soon as possible; this must include long-term measurements of solar radiation, albedo, and terrestrial IR emission; (2) ocean-monitoring capability must be greatly improved; highest priority should be given to measurement of the heat content and field of motion of the mixed layer and of surface wind; and (3) quantitative surveillance of the atmospheric constituents that play a role in the global radiation balance must be instituted.

APPLICATIONS TO FIELDS OTHER THAN METEOROLOGY

The close and effective cooperation between NASA and NOAA has been largely responsible for the development during the past several years of an extremely successful environmental satellite system. Nevertheless, the Panel recognizes that this cooperation has resulted in an almost exclusive focus of attention on defining sensors and using satellite data for operational synoptic forecasting. NOAA is in the unique position of being the collector, the disseminator, the archivist, and the principal user of satellite meteorological data. NOAA also defines meteorological requirements for operational satellite systems. This situation has resulted in the efficient use of satellite weather data for forecast purposes, but in minimal use of these data by other users for other purposes.

Disciplines in which meteorology is an extremely important component (such as environmental quality, agricultural meteorology, hydrology, and oceanography) could benefit from available satellite meteorological data in their research and operational programs. In addition, these data could be used effectively by industry and commerce. Indeed, the potential economic benefit of the use of meteorological data for such purposes may equal or exceed their use for forecast purposes.

There is a substantial need for the development of sensors to measure parameters important to other users; for example, the amount, nature, and intensity of precipitation; soil and snow moisture content; and sea-surface temperatures and winds. None of these data can be obtained with the required accuracy from existing sensors.

Scientists and engineers in fields in which meteorological and climatological factors are important should also have greater voice in the formulation of requirements for meteorological data and sensors as well as in the management of operational systems. Some appropriate mechanism must be found to focus needed attention on such requirements without losing the benefits of the present close cooperation between NASA and NOAA.

RECOMMENDATION - The Panel recommends that formal mechanisms be established to broaden the utility of the meteorological satellite program. The broadening should provide for participation in program planning by users of meteorological data in such fields as agriculture, transportation, hydrology, and oceanography. The operational meteorological system should also be responsive to the needs of such disciplines for real-time data.

HIGH-PRIORITY NEEDS WITHIN PRESENT SYSTEMS

An extensive R&D program in support of operational weather satellites is already in existence. This program has been thoughtfully constructed over a period of many years by a capable, dedicated group of meteorologists and engineers. A substantial group of R&D initiatives is well under way; others are under consideration.

In these circumstances, it would be surprising indeed if the Panel on Weather and Climate should find major deficiencies in the program as a result of this comparatively limited review. Many of the following recommendations are, therefore, designed to emphasize high-priority needs in areas where work is already under way. It is clearly recognized that many of the recommendations will require an extensive R&D commitment over an extended period of time.

IMPROVED SOUNDING OF THE ATMOSPHERE

The primary contribution of operational satellites to weather forecasting is the determination of the vertical structure of the atmosphere, especially temperature and humidity. Present IR soundings indicate the temperature structure with an accuracy of about 2°C or 3°C; an accuracy approaching that of radiosondes (about 1°C) would be more useful. The resolution of present satellite observations in clear air is approximately 40 km, a figure satisfactory for synoptic forecasts.

However, difficulties are encountered when substantial cloud cover exists. The use of microwave sounders will to a considerable extent overcome these problems. The successful operation of a non-scanning microwave sounder on NIMBUS-5 opens the way to development of a combined IR and microwave sounding system and, indeed, such a system is being developed for operational use. Neither the IR nor the microwave sounder, however, locates temperature inversions well, especially the important inversion at the tropopause (the boundary between the troposphere and the stratosphere). A limb-scanning IR sounder is being prepared for launch on NIMBUS-F in late 1974. A test of this instrument on a balloon flight has proved its ability to locate the height of the tropopause and to obtain an accurate temperature profile.

With respect to humidity profiles, the total water vapor in a column is measurable to about 20% accuracy by present vertical sounders, and a future sounder will include two channels for water vapor determination. By 1978 it should be possible to construct a crude two-parameter vertical profile with

an accuracy of 20% to 30%. The sounding, however, will be limited to the middle and lower troposphere, since the upper troposphere is too dry to emit adequate signals in this band. A limb-scanning sounder may make it possible to extend the humidity profile upward from the middle troposphere to the stratosphere.

RECOMMENDATION - The Panel recommends that the vertical temperature sounding capability be improved to approach more closely a 1°C accuracy requirement. The Panel strongly supports the concept of a combined IR and microwave sounder for future operational systems and recommends that the possibility be kept open of adding limb-scanning sounders as well.

IMPROVED GEOSTATIONARY SATELLITES

Geostationary meteorological satellites will become increasingly important in the operational meteorological system. Observational coverage is virtually continuous. These satellites are ideal for frequent monitoring of such phenomena as local severe storms; generally, these platforms are capable of repeated and detailed examination of portions of the earth's atmosphere which are of particular interest or concern. Data from geostationary satellites are of key importance to synoptic forecasts; such information will also be valuable in the display of present-weather information to a wide variety of users.

Four important improvements should be made in the geostationary satellite system:

> IR sounders should be incorporated into the existing satellite system as soon as possible.
>
> Three-axis-stabilized geostationary satellites should be used to replace the existing spin-stablized operational satellites. This improvement would make it possible to view the earth continuously, with a gain in viewing efficiency by a factor of 10 to 20.
>
> Microwave sounders should be added to three-axis-stabilized geostationary satellites as soon as possible.
>
> A low-cost local readout system should be developed to bring the information directly to many users, public agencies and private organizations.

RECOMMENDATION - The Panel recommends that high priority be given to a long-term R&D effort to provide a new generation of geostationary satellites. These improved satellites should be three-axis-stabilized, have the capability to view selectively sectors of the earth's disk, be provided with a low-cost local readout system, and incorporate advanced capability in temperature and humidity sounding.

OPERATIONAL RADIATION-BUDGET OBSERVATIONS

Preparation of synoptic forecasts and climate predictions requires substantially improved understanding of the radiation budget of the earth. Budget determination includes the measurement of solar radiation, the determination of the earth's albedo, and the measurement of outgoing IR emissions. These measurements will ultimately be used to establish parameters for the energy budget in terms of other measurements of the state of the atmosphere, such as the nature and distribution of cloud cover and the vertical structure of temperature and humidity.

Considerable work has already been undertaken in the development of the necessary sensors, and experimental determinations of the earth's energy budget will be taken from NIMBUS-F. However, accurate measurements from space of the earth's radiation balance will not be achieved easily. A host of special problems exists, such as the effect of viewing angle on albedo measurements. In addition, the use of polar-orbiting sun-synchronous satellites would introduce consistent (diurnal) errors into the energy-budget determination. The elimination of such problems will require particular care.

RECOMMENDATION - The Panel recommends that an operational capability to measure the radiation budget of the earth be developed as quickly as possible. Studies should be undertaken to determine the kind of multiple-satellite, multiple-orbit system required to obtain good samplings of local times and of reflectance angles, to permit accurate determination of the average planetary albedo. The operational system must provide long-term (that is, over decades) continuity and consistency of radiation measurements.

MONITORING OCEANS

The ability of the oceans to store, redistribute, and release heat makes them a prime factor in climate prediction. It is therefore vital that the sea-surface temperature and the heat content of the upper layer of the ocean be observed routinely. Also required are estimates of surface winds over the ocean and of near-surface currents. These data are vital to the development of models of climate.

Present measurements of sea-surface temperature, while encouraging, are not accurate enough to be of major use. However, future system improvements promise to provide the accuracy required. Considerable effort must be expended to develop a wind-measuring capability. The estimation of near-surface currents poses an even more difficult problem that has yet to be addressed.

RECOMMENDATION - The Panel recommends that an operational capability be undertaken as quickly as possible to measure climatically important oceanic variables.

MONITORING ATMOSPHERIC CONSTITUENTS, PARTICULATE LOADING, AND AEROSOLS

Theoretical studies have indicated that changes in the composition of the atmosphere with regard to minor constitutents, particulate loading, and aerosols can have a major effect on climate. The measured concentration of carbon dioxide has increased about 25% in the last century. Substantial variations in stratospheric ozone concentration are also suspected. Particulate loading and aerosol concentration are also believed to be increasing, although reliable data are lacking. Clearly, the intelligent management of man's activities requires careful monitoring of the atmosphere in order to establish a baseline, to detect trends, and to detect climatic changes. Satellite remote-sensing techniques provide a possible major contribution to such a monitoring program. A number of promising techniques are to be tested on NIMBUS-G to demonstrate their effectiveness.

RECOMMENDATION - An operational capability to monitor climatically important atmospheric constituents, particulate loading, and aerosols should be undertaken as quickly as possible.

ACCURATE DETERMINATION OF OCCURRENCE AND INTENSITY OF PRECIPITATION, SOIL MOISTURE, AND WATER CONTENT OF SNOW

Microwave emission has been used experimentally to delineate areas where heavy precipitation is occurring. Such observations are most easily made over the ocean where there is substantially lower surface emission at these frequencies. Results have been sufficiently encouraging to warrant the development of an R&D program to measure precipitation on a world-wide basis. Such observations would be particularly valuable not only in meteorology but also in a variety of other disciplines, such as water resources and agriculture. Soil moisture and the water content of snow may also be measurable through the use of microwaves. The difficulties of instrumentation are many. Nevertheless, these types of observations, which can best be made from meteorological satellites, would provide invaluable information. An appropriate R&D program should be initiated to determine the feasibility of such measurements.

RECOMMENDATION - The Panel recommends an R&D effort to produce sensing and processing systems to provide information on the occurrence and intensity of precipitation and on the moisture content of soil and snow cover.

IMPROVED DETERMINATION AND EVALUATION OF THE ACCURACY OF EARTH OBSERVATIONS FROM SPACE

It is essential that users have access to detailed information concerning the accuracy of meteorological measurements derived from satellite sensor systems. A series of carefully planned ground-air-verification experiments will be needed to compare the satellite-based observations with those obtained by the various land-based techniques. Information should also be provided on the horizontal and vertical resolutions of the sensor systems and the derived observations.

RECOMMENDATION - The Panel recommends that observations obtained or derived from satellite sensors be checked regularly against those from ground-based observing methods with known degrees of accuracy. Results of such verification tests should be published and furnished to users along with the data. Information on the effective horizontal and vertical resolutions of the observations should be provided as well.

DATA MANAGEMENT

It is evident that meteorological satellites of the future will necessarily provide information to a much broader category of users than does the present system. New data-management techniques will have to be implemented to disseminate appropriate data to a variety of users on a current basis. In addition, the categorizing and storing of historical data for climate-prediction models and other future uses will need to be more comprehensive and flexible. This is by no means a trivial problem. The vast amount of raw data transmitted to the ground by weather satellites makes it mandatory to undertake a substantial amount of processing before the data are stored. A great deal of thought must go into determining the optimum method and system of processing in order to achieve maximum compression of data with a minimum loss of flexibility to potential users. In studying this problem, the needs of fields other than weather forecasting must be fully considered. Finally, in the design of the total system, consideration must also be given to the output of certain standard products such as average-cloud charts, mean temperature, or average IR emission.

RECOMMENDATION - The Panel recommends that a comprehensive data-management scheme be implemented to utilize and store more effectively the vast quantities of information being obtained by meteorological satellites. The data system should function to (1) provide meteorological information to the broad category of users not directly in weather forecasting, (2) catalog and store information for future use, and (3) design, develop, disseminate, and store sets of information products derived from satellite data.

USE OF SPACE SHUTTLE AND SPACELAB

The space shuttle and spacelab will be useful for three kinds of activity important to meteorology and climate:

1. As a convenient test bed for very exploratory experiments, such as high-power laser Raman spectroscopy to determine the gas composition of the stratosphere, high-power laser experiments to map stratospheric aerosol layers, and active radar experiments to map precipitation intensity.

2. As the only way now contemplated of providing means to obtain accurate absolute calibration of radiation sensors observing both incoming solar and out-going terrestrial radiation. Secondary or even primary laboratory-type radiation standards can be carried, perhaps once per year, on space-shuttle flights to obtain accurate observations against which to calibrate the satellite instruments.

3. As a means of conducting zero-g experiments. A series of specialized zero-g cloud-physics experiments has been proposed, which is the subject of a current feasibility study. These experiments look promising but it is premature to draw any firm conclusions concerning their importance to cloud-physics problems and their desirability for inclusion in the spacelab program.

In addition, the space shuttle is expected to have adequate performance for emplacement, servicing and replacement of operational low-altitude weather satellites. Tug service is required for emplacement of geostationary weather satellites. These services will be viable only if means can be provided to share shuttle and tug payload-space and costs so that services are affordable.

FUTURE APPLICATIONS

The space applications program in meteorology is a mature effort. In addition to the operational system, a well developed R&D program exists. Most novel ideas for meteorological observations from space have at least been discussed. Under the circumstances, it would be surprising indeed if the present Panel were able to identify major new opportunities for future development. It should be noted, however, that some of the recommendations set forth herein involve advanced technology and may require two or more decades to implement fully.

This report would be deficient, however, if additional comments were not presented with regard to observational techniques which look promising for the future but have not been mentioned in the recommendations of the Panel. The first of these is radar, which might be used effectively in the global measurement of precipitation occurrence and intensity. Problems of background interference and power demand must be overcome. Doppler radar conceivably could be used to measure the wind velocity in clouds. A related long-term potential is the use of lasers and the Doppler principle for wind determination in clear air. A different kind of possibility is the establishment of an earth-oriented meteorological observatory on the moon. A simple first experiment for such an observatory might be the measurement of the earth's albedo.

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SUMMARY

Many of the important recommendations made in the 1967-68 Summer Study on Space Applications* have been implemented and have become or are now becoming integral parts of the U.S. meteorology program. Other recommended developments have not yet reached maturity. They are still in the research and development (R&D) phase, although the outlook is promising that they will be incorporated into the next generation of operational satellite systems. The emergence of an international program, the Global Atmospheric Research Program (GARP), with specific observational requirements has helped to stimulate and accelerate much of this development. The First GARP Global Experiment (FGGE) will provide in 1978-79 an intensive programmatic test of the applicability of these systems to specific research and to prototype operational needs on a global basis.

New needs are now apparent that are much broader than the GARP observational experiments and also encompass a much broader range of users than the weather-forecasting community. The Panel on Weather and Climate has specific recommendations in the following areas:

PRESENT-WEATHER DISPLAY

Current and projected satellite systems provide the possibility of supplying timely, nearly instantaneous monitoring of small to medium weather systems whose occurrence impacts diverse industrial, commercial, and agricultural communities, as well as the general public. The projected three-axis-stabilized geostationary satellite with high-resolution imaging and sounding capability will be a central observational tool for such applications. The information from this system will be greatly enhanced in value if coupled with economical equipment for direct ground readout and processing and with means of automatic dissemination of a variety of products to end users. *The Panel recommends R&D of such a capability for public information distribution.*

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*National Research Council. *Useful Applications of Earth-Oriented Satellites: Report of the Panel on Meteorology* (Panel 4). National Academy of Sciences, Washington, D.C., 1969.

SHORT-RANGE FORECASTS (2 to 12 HOURS)

The advanced geostationary-satellite system could be used in conjunction with land-based systems to identify and develop very short-range forecasts of severe storms and weather systems that produce floods, heavy snows, and other events of important impact.

SYNOPTIC FORECASTS (1 to 7 DAYS)

The First GARP Global Experiment (FGGE), scheduled in 1978-79, is designated to study the synoptic range of weather systems (systems of 1 to 7 days in duration). Projected performance of sensor systems for that period indicates that the FGGE requirements will be met only marginally. *The Panel recommends continued R&D efforts on remote-sensing techniques to assure that FGGE requirements will be met.*

LONG-RANGE WEATHER AND CLIMATE PREDICTION

Long-range weather and climate prediction is an important area of activity which is now receiving much attention and is ripe for scientific investigation. Satellite systems will make it possible to observe and monitor on a long-term basis many of the physical factors thought to be critical to establishing the mean or statistical state of the atmosphere for seasons, years, or decades. Many of these factors are manifested in their effects on the radiation budget of the land-air-ocean system. Hence, critical attention must be paid to calibration, intercomparison, and periodic *in situ* recalibration of radiation sensors on spacecraft. *The Panel recommends initiation of observation of a number of these climatic factors; an intensive program to investigate the time and space sampling needed to produce meaningful average values for large regions, as well as for the entire globe; and the development of comparison and in-flight recalibration procedures that will make it possible to identify secular changes that may be related to climatic trends or variations.* Among such important long-term climatic factors are the incoming and outgoing radiation; the planetary albedo; the heat content of the mixed layer in the oceans; the distribution of clouds at low, middle, and high levels; and any significant changes in surface features such as vegetation, land use, and snow and ice cover.

OTHER USES OF WEATHER DATA

Much of the information gathered by satellites for meteorological forecasting use can also be processed for use by other groups. Moreover, there are additional parameters that could be obtained that would be of great use in agriculture and hydrology, to name but two fields. *The Panel recommends that additional user groups be brought into the decision-making process of setting priorities for the development of new observing techniques and for the processing and storing of meteorological data, so that as wide as possible a spectrum of user groups can benefit from the space-based meteorological satellite systems of the future.*

INTERFACE WITH SPACE TRANSPORTATION SYSTEM

The Panel believes that the space shuttle and spacelab can contribute uniquely to solution of the radiation calibration problem by permitting secondary and (in the future) even primary standards to be used for in-flight calibration of satellite sensor systems. Spacelab can also be used for accelerating R&D sensor system development.

The space shuttle is expected to have adequate performance for emplacement, servicing, and replacement of operational low-altitude weather satellites. Tug service is required for emplacement of geostationary weather satellites. These services will be viable only if means can be provided to share the shuttle and tug payload-space and costs so that the services are affordable.